

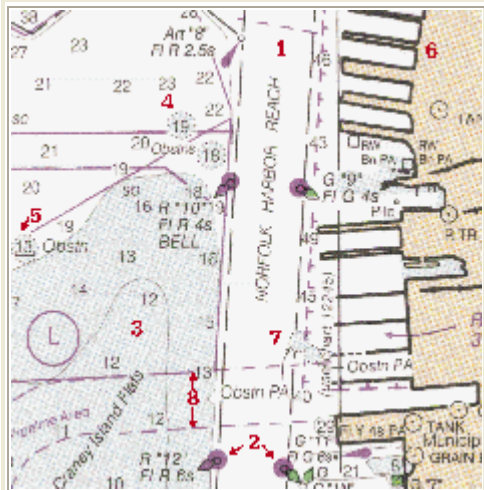
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Behind the Accuracy of Electronic Charts--*What Every Mariner Should Know about Electronic and Paper Charts*

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Electronic charts that integrate real-time GPS positioning with nautical charting data have been a major development in advancing navigational technology over the past 15 years. An electronic chart is an important tool that can enhance the mariner's situational awareness on the bridge. Instead of spending an inordinate amount of time obtaining and plotting a position fix on a paper chart, an electronic chart frees the mariner to analyze a situation and take appropriate action. A position fix plotted on a paper chart shows you where you were--a position displayed on an electronic chart shows you where you are. As is the case with any navigational instrument, the user must be mindful of the capabilities and the limitations of the electronic chart in use. In particular, the mariner should understand that nautical chart data displayed on such systems possess inherent accuracy limitations. Many of these limitations have migrated from the paper chart into the electronic chart.

For the purpose of this discussion, the term "electronic chart" refers to a system that has four general components: 1) computer hardware, 2) real-time positioning (typically GPS) and other sensors, 3) electronic chart data and 4) software that displays and manipulates both chart data and real-time sensor input. There are two types of electronic charts. The Electronic Chart Display and Information System (ECDIS) is the only internationally standardized form of electronic chart. All other types of electronic charts can be regarded, generically, as Electronic Chart Systems (ECS). For an electronic chart to be considered an ECDIS, it must comply with the performance standards for ECDIS established by the International Maritime Organization (IMO). Under development for over 10 years, the IMO Performance Standards for ECDIS specify the components, features and functions of a system in which the primary purpose is to contribute to safe navigation. While this paper will focus on the inherent accuracy issues associated with electronic chart data, other source of errors will also be discussed briefly.



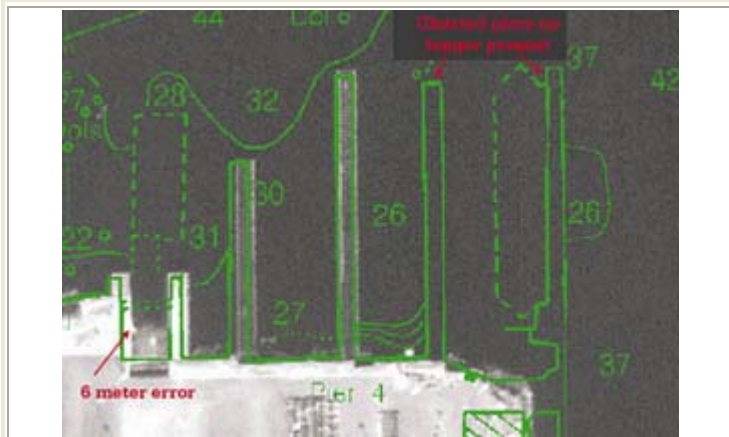
Source of chart information: 1) Corps of Engineers provides federal channel limits and surveys, 2) Coast Guard provides aids to navigation information, 3) NOAA and contractors conduct hydrographic surveys outside federal projects, 4) Least Depths on obstructions accurately determined by NOAA, 5) Wire drag cleared depth by NOAA (pre-1987), 6) NOAA's National Geodetic Survey provides shoreline, 7) Position Approximate obstructions reported through Local Notice to Mariners and 8) Holder of pipeline permit provides NOAA with as-laid drawings.

Electronic chart software provides for geographic registration and display of electronic charting data. The process is straightforward and should have negligible error. Most electronic charts display an icon representing the vessel's position. Some ECS software enables the user to input a vessel's dimensions and GPS antenna location. On larger vessels, the relative position of the GPS antenna aboard the ship can be a potential source of error when viewing the vessel icon in an ECS.

There are two general categories of electronic chart data: Raster Nautical Charts (RNC) and vector charts. RNCs are scanned digital images of paper charts. In 1994, the National Oceanic and Atmospheric Administration's (NOAA) Office of Coast Survey scanned its suite of 1,000 paper charts that covers the coastal waters of the U.S. and its territories. Raster Chart Display Systems (RCDS), a type of ECS, show real-time vessel positions projected on the image of the chart. While these systems have impressive utility, they have limited ability to provide danger warnings to the mariner. This is due to the fact that raster data has

little inherent intelligence. For example, the computer is unable to differentiate between a series of pixels that represent a buoy or those that portray a wreck. Likewise, an RCDS does not have the ability to recognize the charted depth of water and, consequently, cannot give a warning if the vessel is headed for a dangerous shoal.

A vector chart is a database that contains points, lines and polygons that correspond to features on the chart. Each item in the database possesses attribution in conformance with a feature catalog. Within a vector database, a buoy might possess the following characteristics: latitude, longitude, color, number, date established and light list number. In addition to point features, depth and other polygon areas can be defined. The database nature of vector data enables electronic chart software to recognize that the vessel is located in a position with a certain charted depth of water. A warning can also be issued that, based on present course and speed, the vessel may encounter a dangerous depth area sometime in the future. An electronic chart using vector data can also have the ability to detect the vessel crossing an important maritime boundary, such as a traffic separation scheme or a marine protected area.



The current NOAA raster chart shown in green, is overlaid on IKONOS satellite imagery acquired in February 2000. Charted shoreline, which is based on a 1970 photogrammetric survey, shows major discrepancies.



SevenCs electronic chart software displays NOAA ENC in Valdez, Alaska. In this simulation (above), concentric circles represent the vessel position. The orange triangle warns the mariner that trouble lies ahead on Bligh Reef.

Electronic chart accuracy is, for the most part, dependent on the accuracy of the chart information being displayed and manipulated. Most raster and vector-based electronic charts used in the coastal waters of the U.S. are based on NOAA paper charts. For example, the official NOAA raster chart, sold by Maptech, is identical to the same edition of the corresponding paper chart.

Other vendors may scan NOAA paper charts (which are not copyrighted) and make their own suite of raster charts. Likewise, companies are free to create a vector product from a NOAA paper chart. It should be noted that some special-purpose ECSs use data that are not based on NOAA paper charts. For example, they may utilize actual hydrographic survey data or dredged channel limits obtained from the U.S. Army Corps of Engineers. The following discussion pertains only to electronic charts derived from NOAA paper charts.

Before the advent of GPS, chart makers were secure in their knowledge that the horizontal accuracy of features portrayed on a paper chart was more than adequate to serve the mariner's needs. Hydrographic surveyors used sextants, theodolites and microwave positioning systems to position near-shore features. Horizontal accuracy standards for hydrographic and photogrammetric surveys were specified in relationship to the largest-scale chart. Twenty years ago, mariners were typically obtaining position fixes using radar ranges, visual bearings or Loran C. Generally, these positioning methods were an order of magnitude less accurate than the horizontal accuracy of the survey information portrayed on the chart. Many of us were quite satisfied when we plotted a fix with three lines of position that resulted in an equilateral triangle whose sides were two millimeters in length at a chart scale of

Before the advent of GPS, chart

1:20,000. In real world coordinates, the triangle would have 40-meter sides. Close enough!

The nautical charting world has been turned upside down in the past 20 years. Although the Coast Guard's DGPS has a stated horizontal accuracy of ± 10 meters (95 percent), many mariners are claiming 3-meter or better accuracy with DGPS. With selective availability set to zero, the most basic GPS receiver in a non-differential mode may offer 10-15 meter horizontal accuracy. Some sophisticated survey receivers now advertise sub-meter accuracy. However, it is not unusual to hear stories about mariners moored at the pier and the vessel icon from their electronic chart plots on the pier. Likewise, many mariners transmitting a range that marks the centerline of a channel report that their electronic chart vessel icon plots on the edge or outside the channel. Mariners now expect, just as they did 20 years ago, that the horizontal accuracy of their charts will be at least as accurate as the positioning system available to them. Unfortunately, any electronic chart based on a paper chart, whether it is raster or vector, will never meet that expectation.

Source Data Deficiencies

The overall horizontal accuracy of data portrayed on paper charts is a combination of the accuracy of the underlying source data and the accuracy of the chart compilation process. Most paper charts are generalized composite documents made up of survey data that have been collected by various sources over a long period of time. In general, NOAA and its private sector contractors conduct hydrographic and photogrammetric surveys in areas outside the limits of federal project areas. The Army Corps of Engineers provides NOAA with survey drawings that are used to chart federal channels. The U.S. Coast Guard furnishes NOAA with positions of aids to navigation. In addition, the Coast Guard's local notice to mariners publishes information on new wrecks, obstructions and other features that affect the chart. The U.S. Navy, the National Imagery and Mapping Agency (NIMA), the U.S. Geological Survey, the U.S. Power Squadrons, the U.S. Coast Guard Auxiliaries, port authorities and private surveyors are other sources of information.

A given chart might encompass one area that is based on a lead line and sextant hydrographic survey conducted in 1890, while another area of the same chart might have been surveyed in the year 2000 with a full-coverage shallow-water multi-beam system. In general, hydrographic surveys inducted by NOAA and the Corps of Engineers have always been to the highest standards. Both agencies have typically used the most accurate hydrographic survey instrumentation available at the time of the survey. While survey positioning methods have changed over the years, standards have generally been such that surveys were conducted with a positioning accuracy of better than .75 millimeters at the scale of the chart. Therefore, on a 1:20,000-scale chart, the survey data was required to be accurate to 15 meters. Features whose positions originate in the local notice to mariners, reported by unknown source, are usually charted with qualifying notations like position approximate (PA) or position doubtful (PD). The charted positions of these features, if they do exist, may be in error by miles.

The above discussion addresses the horizontal accuracy of source data submitted to NOAA. However, the adequacy with which that source data reflects today's real world conditions, in particular depths and underwater features, is an entirely separate issue. Over 50 percent of the depth information found on NOAA charts is based on hydrographic surveys conducted before 1940. Surveys conducted with lead lines or single-beam echo sounders sampled a small percentage of the ocean bottom. Due to technological constraints, hydrographers were unable to see between the sounding lines. Depending on the water depth, these lines may have been spaced at 50, 100, 200 or 400 meters. Today, as NOAA and its contractors re-survey areas and obtain full-bottom coverage, uncharted features (some that are dangers to navigation) are routinely discovered. These features were either: 1) not detected on prior surveys, 2) manmade objects, like wrecks and obstructions, that have appeared on the ocean bottom since the prior survey or 3) the result of natural changes that have occurred since the prior survey.

In a similar manner, the shoreline found on most NOAA charts is based on photogrammetric or plane table surveys that are more than 20 years old. In major commercial harbors, the waterfront is constantly changing. New piers are being constructed and old piers are being destroyed. Some of these manmade changes are added to the chart when the responsible authority provides NOAA with as-built drawings. However, many changes are never reported to NOAA and therefore do not appear on the chart. Natural erosion along the shoreline, subsidence and uplift also render charted shoreline inaccurate in many areas.

Chart Compilation Inaccuracies

Another component of horizontal chart accuracy involves the chart compilation process. Before NOAA's suite of charts was scanned into raster format in 1994, all chart compilation was performed manually. Projection lines were constructed and drawn by hand and all plotting was done relative to these lines. Cartographers graphically reduced large-scale (high-detail) surveys or engineering drawings to chart scale. Very often these drawings were referenced to state plane or other local coordinate systems. The data would then be converted to the horizontal datum of the chart (e.g., the North American 1927 (NAD27) or the North American Datum 1983 (NAD83). In the late 1980's and early 1990's, NOAA converted all of its charts to NAD83. In accomplishing this task, averaging techniques were used and all of the projection lines were re-drawn manually. When NOAA scanned its charts and moved its cartographic production into a computer environment, variations were noted between manually constructed projection lines and those that were computer generated. All of the raster charts were adjusted or warped so that the manual projection lines conformed to the computer-generated projection. In doing so, all information displayed on the chart was moved or adjusted.

Many electronic chart positional discrepancies that are observed today originate from graphical chart compilation techniques of the past. The manual application of survey data of varying scales to the fixed chart scale was a source of error that often introduced biases. In the past, source information at large scales would often have to be reduced with a copy machine so it could be overlaid and transferred to the master version of the chart. Today, when NOAA survey crews and contractors obtain DGPS positions on prominent

shoreline features, and compare those positions to the chart, biases may be found that are on the order of 2 millimeters at the scale of the chart (e.g., 20 meters on 1:10,000-scale chart). High accuracy aerial photography reveals similar discrepancies between the true shoreline and the charted shoreline. It stands to reason that other important features such as dredged channel limits and navigational aids also exhibit these types of biases. Unfortunately, on any given chart, the magnitude and the direction of these discrepancies will vary in different areas of the chart. Therefore, no systematic adjustment can easily be performed that will improve the inherent accuracy of the paper or electronic chart.

Some mariners have the misconception that because charts can be viewed on a computer, the information displayed has somehow become more accurate than what appears on paper. It is ironic that electronic charts now give the mariner the ability to zoom in to charted depths that are based on surveys conducted 100 years ago. Some mariners believe that vector data is always more accurate than paper or raster data. Clearly, if an electronic chart database is built by vectorizing a paper chart, it can be no more accurate than the paper chart.

Addressing the Accuracy Problem

A national suite of highly accurate electronic charts will be a primary cornerstone of a safe and efficient Marine Transportation System (MTS) in the 21st century. With the volume of commercial traffic in U.S. waters expected to double in the next 20 years, mariners will become increasingly dependent on electronic charts for route planning and transit monitoring in congested waters.

NOAA is in the process of building a new charting database that will address some of the inadequacies of today's electronic charts. The Electronic Navigational Chart (ENC) is a vector database of chart features being built to the International Hydrographic Organization's S-57 standard. NOAA's Office of Coast Survey, as the U.S. national hydrographic office, is exclusively responsible for production and authorization of ENC data in U.S. waters. In order for an electronic chart to gain type approval as an ECDIS, it must be fueled by ENC data. However, ENC data is not only for ECDIS use. ENCs can fuel any ECS that reads the S-57 format.

NOAA's approach to building ENCs addresses the horizontal accuracy issues raised in this paper. The ideal and most accurate way to build an ENC is to recompile the chart from all of the original source material. Unfortunately, the process is impractical as it is far too labor intensive. Instead, ENCs are being compiled from source on those features that are deemed to be navigationally significant. Army Corps of Engineers' federal project limits have been captured from large-scale drawings. The precise coordinates of channel limits are being woven into the ENC. Likewise, high-accuracy positions are being used to chart Coast Guard aids to navigation.

Positions of all wrecks, obstructions and other hazards that appear on the chart have been researched to obtain original positions. These data are also being incorporated into the ENC. The remaining data are being vectorized from the paper chart.

Once ENCs are built, they will be enhanced with higher-accuracy data over time. High-resolution shoreline is being incorporated into the ENC as new photogrammetric surveys are being conducted. Likewise, depths from new hydrographic surveys will gradually supersede depths that originated from old surveys on the paper chart. Increasingly, NOAA is receiving source information in a digital format from the Army Corps of Engineers and the Coast Guard. As more digital data are received in geographic coordinates (latitude and longitude), the chart compilation process will become less graphical and more accurate.

Like other hydrographic offices around the world, NOAA has struggled with the complexities of building ENCs. With limited resources, a phased approach is being undertaken. Two hundred charts have been identified that cover the 40 major commercial ports in the U.S. To date, 90 ENCs have been built and are being updated as new source data are received. By October 2001, 135 ENCs are projected to be complete. Several ENC test data sets have been complete. Several ENC test data sets have been released in New Orleans, Tampa, St. Mary's River and Houston. At this time, various methods for distributing ENCs are being explored, however, a plan has not yet been finalized.

Conclusion

Technological advancements in hydrographic surveying and chart compilation are significantly improving the accuracy of electronic chart data. Electronic charts are being constructed in Geographic Information Systems where the original geographic coordinates of source information are preserved. In the future, NOAA envisions that an accurate, up-to-date ENC vector database will serve as the foundation for a host of charting products produced by the private sector. Electronic chart manufacturers will access this database and value-add to it. For example, some vendors may develop software to display ENC data coupled with aerial photography; others may enhance the ENC database with additional attribution and create other products. Ultimately, NOAA envisions printing paper charts from the ENC database. Mariners in the 21st century expect highly accurate electronic charts. NOAA is working toward that goal.

References

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